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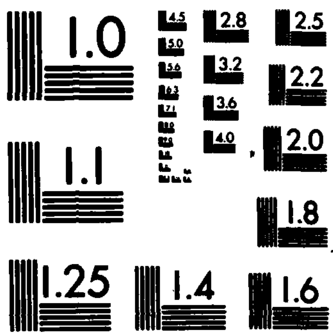

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HUMAN RESOURCES

VISUAL PHENOMENA PRODUCED BY
BINOCULARLY DISPARATE DYNAMIC VISUAL NOISE

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A series of four experiments addressed several perceptual problems associated with the use of binocularly disparate stimuli. The stimulus used in all four experiments was the dynamic visual noise (DVN) stereophenomenon produced by viewing a detuned television receiver with the input to one eye attenuated by a light filter. The result is the percept of several counterdirectional dot-planes separated in depth.

In Experiment I, we studied the movement aftereffect (MAE) induced by the moving dot-planes of the DVN stereophenomenon. MAE magnitude was independent of the interocular intensity difference and of the time spent viewing the inducing movement.

In Experiment II, binocular rivalry was induced by placing a red filter over the dominant eye while both eyes viewed the DVN display. Under these conditions the perception of dot-planes moving at various distances from the observer persisted over the entire rivalry cycle.

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Experiment III was an attempt to quantify and interpret the observation that the velocity of the moving depth planes of the DVN stereophenomenon increases during visual tracking of those planes. Recorded eye movements showed consistent acceleration, with a maximum velocity ten times greater than that estimated during fixation of a stationary point superimposed on the DVN.

Finally, in Experiment IV, steady-state vergence and accommodation were measured to the proximal and distal depth planes produced by viewing the DVN stereophenomenon. Both vergence and accommodation were elicited although only a significant difference in vergence to the two depth planes was found.

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SUMMARY

The use of helmet-mounted displays in flight simulation requires that different visual stimuli be presented to the two eyes. Such disparate stimulation may result in perceptual problems which could adversely affect simulator training. The purpose of the basic visual research reported here is to further elucidate the visual mechanisms underlying movement aftereffects (Experiment I), binocular rivalry (Experiment II), perceived visual acceleration (Experiment III), and vergence and accommodation to perceived depth (Experiment IV). Each of these phenomena was induced by a form-free texture stimulus perceived as moving in planes located at various distances from the observer.

PREFACE

The research reported here was performed in support of the Aircrew Training Thrust at the Operations Training Division of the Air Force Human Resources Laboratory, Williams Air Force Base, Arizona. The purpose of the research is to elucidate the basic mechanisms underlying visually guided behavior in flight simulators and specifically those using helmet-mounted displays.

Portions of Experiments I and II and all of Experiment III were performed in the Man-Vehicle Laboratory at the Massachusetts Institute of Technology. Experiment IV was performed at The Visual Sciences Department of the State University of New York College of Optometry where Dr. Kenneth Ciuffreda provided helpful assistance and use of laboratory facilities.

This research was supported by Air Force Contracts F33615-81-C-0005 and F33615-81-K-0011. The latter contract was monitored by Dr. Thomas Longridge of AFHRL/OT who contributed immeasurably to its successful completion.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

EXPERIMENT 1: A PURELY CENTRAL MOVEMENT AFTEREFFECT INDUCED BY BINOCULAR VIEWING OF DYNAMIC VISUAL NOISE

Introduction

The dynamic visual noise (DVN) stereophenomenon is the perception of depth and coherent motion that results when an interocular intensity difference is introduced during the binocular viewing of dynamic visual noise (Falk & Williams, 1980; Ross, 1974; Tyler, 1974, 1977). The binocular disparity resulting from the intensity difference transforms the random pattern of dots of the dynamic visual noise (DVN) into a distribution of coherently moving dot-planes which appear separated in depth. It has been noted that under certain stimulus conditions one of the moving dot planes appears most distinct (Falk & Williams, 1980) and, hence, that plane can be used as a visual stimulus independent of the other planes. For example, Zeevi and Medina (1984) showed that the perceived velocity associated with this single dot-plane could serve as a stimulus for smooth eye movements.

Classical movement aftereffects (MAEs), such as the waterfall illusion, are induced by stimulus movement on the retina and thus may be classified as peripheral MAEs. Another type of MAE can be observed under binocular or dichoptic conditions (Anstis & Duncan, 1983; Barlow & Brindley, 1963; Favreau, 1976). In this case, too, movement information exists at the retinal level, although the central aspect of the MAE becomes evident only under appropriate binocular testing procedures. A third type of MAE, here referred to as a purely central MAE, is produced by perceived movement which does not exist at the retinal level (Anstis & Moulden, 1970; Papert, 1964) Since the movement associated with the DVN stereophenomenon is centrally produced, any MAE induced by it may be considered a purely central MAE. The studies of Papert and of Anstis and Moulden have indicated that the purely central MAE is qualitatively different from either peripheral or central (binocular) MAEs. For instance, purely central MAEs are shorter for a given inducing time and are more sporadic and less pronounced than are the peripheral or central MAEs.

In this experiment, the unique properties of the purely central MAE were further investigated, and some of its characteristics were quantified. Specifically, the relationship was established between the velocity of the inducing movement and that of the resulting MAE.

Method

Observers. Data were obtained from three emmetropic, male observers, JH, DW, and GG, who were 21, 22, and 32 years of age, respectively. The appearance of the aftereffect was confirmed by nine additional observers while one observer failed to perceive movement or depth in the DVN display.

Apparatus. The DVN stimulus was produced by a detuned television receiver (Sony Trinitron Color Monitor, Model CVM-1225) with its screen masked to give a 17 degree (horizontal) x 13 degree rectangular field at a viewing distance of 0.8 meter. The observers viewed the DVN stimulus through a large beamsplitter that allowed a moving spot to be binocularly superimposed on the DVN display. The spot was produced on an oscilloscope by a function generator, and its velocity was controlled by the observer. The mean luminance of the DVN display was 28 foot-lamberts (fL) as viewed through the beamsplitter. An interocular luminance difference was produced by neutral density filters placed in front of the right eye of each observer. Chin and head rests were provided for the observers who were asked to fixate a small black spot placed on the TV monitor screen.

It is well established that eye movements affect the perceived velocity associated with the DVN stereophenomenon (Tyler, 1974; Ward & Morgan, 1978; Zeevi & Medina, 1984). The observers were, therefore, instructed to maintain fixation at the center of the DVN display while making their aftereffect velocity settings. The observers were questioned throughout each experimental session as to whether they maintained fixation, and those trials for which fixation was not maintained were discarded. Eye position was monitored objectively in related experiments (although not for the three observers tested here) wherein it was established that the DVN stereophenomenon and its associated MAE could be perceived without eye movements.

Procedure. Three observers participated in the study. After 4 to 5 minutes of adaptation to the ambient illumination and the dynamic noise produced by the TV monitor, a neutral density filter was placed before the observer's right eye. The observer first set the depth of the superimposed moving spot to be coplanar with the most distinct dot-plane (i.e, the plane used as the movement stimulus). While fixating the center of the DVN display, the observer adjusted the velocity of the moving spot to match that of the moving dot-plane. A total of eight settings were made for each interocular luminance difference over the course of four experimental sessions. Within each session seven luminance differences corresponding to neutral densities of 1.0, 1.3, 1.5, 1.7, 2.0, 2.3, and 2.5 were presented randomly. The MAE was induced by allowing the observer to view the coherent motion of the recessed

plane for 20 seconds and then suddenly removing the attenuating filter. The observer attempted to match the velocity of the moving spot, which was now set coplanar with the DVN display, to that of the resulting MAE. Because the MAE lasted only a few seconds, several trials were needed for each setting with the observer making adjustments such that the velocity of the MAE was gradually approached. Four settings were obtained for each interocular luminance difference over the four experimental sessions.

Results

When viewing the DVN display with a neutral density filter over one eye, all three observers reported the perception of both movement and depth defined by a distribution of recessed planes of dots (pixels) moving in the direction of the unfiltered eye and a complementary distribution of protruding planes of dots moving in the opposite direction. In accord with the observations of Falk and Williams (1980), most of the observers reported that the farthest dot-plane appeared most distinct. This percept was, in fact, a criterion for selecting the three observers who participated in the present MAE study.

The solid circles in Figure 1 show data, for all three observers, relating the velocity of apparent movement of the dots in the DVN display and the interocular luminance difference. An analysis of variance indicated that dot velocity was an increasing function of the amount of neutral density attenuation placed in front of the right eye ($F(6,12) = 5.50$, $p < .01$).

After viewing the recessed plane for 20 seconds, all observers saw an MAE when the inducing filter was removed. It appeared as a unidirectional surge of the DVN field in a direction opposite that of the inducing dot-plane. The MAE lasted only 1 to 3 seconds, and no perception of depth was associated with it. The duration and magnitude of the MAE did not depend on the time spent viewing the movement associated with the DVN. The open circles of Figure 1 show the relationship between the interocular luminance difference and the velocity of the MAE. The analysis of variance indicated that (a) the MAE was judged faster than the apparent motion which induced it ($p < .05$), as can also be observed from the upward shift of most of the MAE data points in Figure 1, and (b) that the velocity of the MAE was independent of the interocular luminance difference ($F(6,12) = 1.53$, $p > .25$). That is, unlike the motion effect, there was no significant trend in the velocity of the MAE as a function of the interocular luminance difference.

If the velocity of the purely central MAE decays over time, it would consist of a range of velocities which might preclude an accurate estimation of its velocity by the observers. To compare the variability

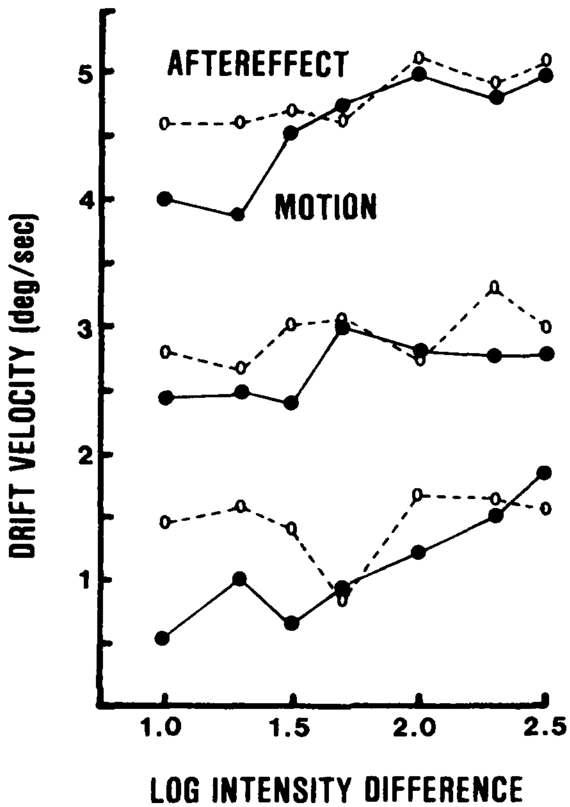

Figure 1. The magnitude of the motion aspect of the DVN stereophenomenon (filled circles) and its associated aftereffect (open circles) both plotted as a function of the interocular intensity difference used to produce the apparent movement stimulus. Although both the movement and its aftereffect increase as a function of the interocular intensity difference, the change in the magnitude of the aftereffect is not statistically significant. The data are from three observers, GG (top), JH (center), and DW (bottom). The data shown for GG are correctly placed along the ordinate while those for JH and DW have been shifted downward by 1 and 3 degrees per second, respectively. Standard deviations are provided in Table 1.

in MAE velocity estimation with that in estimating the induction field velocity, Table 1 summarizes the mean and range of standard deviations about the data points of each curve of Figure 1. These data indicate that the observers could estimate MAE velocity as accurately as they could estimate the velocity of the movement stimulus. It is not known whether the observers estimated the average or peak velocity of the MAE, but they were able to do it consistently, and the conclusions are equally valid for either case.

Table 1. Summary of Data Standard Deviations

		Motion	MAE
GG	mean	0.56	0.62
	range	0.44 - 0.69	0.46 - 0.78
JH	mean	0.48	0.65
	range	0.34 - 0.57	0.48 - 0.79
DW	mean	0.53	0.70
	range	0.46 - 0.58	0.59 - 0.78

It might be argued that the MAE reported here is due to a difference in the adaptational state of the two eyes at the moment the neutral density filters are removed. In order to obviate this possibility, control studies were performed in which one eye was dark adapted for 10 minutes while the other eye viewed either the DVN display or even more intense room illumination. Even under these extreme conditions of differential adaptation, no MAE was ever seen when the dark adapted eye was uncovered.

Discussion

There are several notable differences between either peripheral or binocular MAEs, produced by stimulus movement on the retina, and what we have called purely central MAEs produced by cyclopean stimuli which are themselves the result of binocular interaction. Papert (1964) produced purely central movement stimuli with a stereocinematogram made up of

individual frames composed of random dots. Each eye alone saw a DVN field while the images seen by the two eyes stereoscopically were correlated to produce a bar which appeared to protrude from the surrounding noise and which moved downward. Papert found that such a stimulus produced a central MAE that was shorter for a given inducing time and was more sporadic and less pronounced than were the peripheral MAEs. Anstis and Moulden (1970) made a further experimental distinction between binocular and purely central (they called them dichoptic) MAEs. They used an ingenious stimulus consisting of a ring of lights which produced a circular phi-movement; in one direction for each eye viewing it separately and in the opposite direction for the two eyes viewing it together. They, too, noted that the central MAE was of shorter duration and less pronounced than was the monocular MAE. The observations on the DVN stereophenomenon MAE in the present study are consistent with those of Papert and of Anstis and Moulden and, in addition, make evident several quantitative differences between purely central MAEs and more conventionally induced MAEs. The data of Figure 1 show that the magnitude of the purely central MAE is independent of the velocity of the inducing stimulus and that the magnitude of the purely central MAE is greater than that of the movement which produced it.

The DVN observed with interocular intensity difference gives rise to a percept of movement coupled with depth. How is it possible then that the two counterdirectional distributions of moving dot-planes induce a directional MAE decoupled from depth information? The present study indicates that, out of the distribution of perceived moving planes, the farthest one appears to be most distinct and, as such, is attended by most of the observers. The aftereffect is associated with this plane, and aftereffect velocity is counterdirectional to that of the inducing field. Further, since just one moving plane is associated with the aftereffect, the necessary substrate for depth information does not exist.

The contention here is that the DVN stimuli used in the present study are analogous to those used by Papert (1964) and by Anstis and Moulden (1970) in that all are cyclopean in nature and thus induce an MAE without stimulus movement on the retina. However, unlike the movement stimuli used in those previous studies, the DVN stimulus in the present study is not associated with either peripheral or central form or edge information. The fact that the results here are qualitatively similar to those obtained using cyclopean form stimuli suggests that the neural locus of the present MAE is central to the point where form and motion information are separated for independent processing. On the other hand, any differences between these stimuli and those of Papert or of Anstis and Moulden might be expected to appear only in a comparison of quantitative MAE data that, at present, do not exist for cyclopean form stimuli. In any case, at least for the study of purely central MAEs, there appears to be some advantage in using DVN inducing stimuli since they are processed exclusively by movement channels.

The differences between binocular MAEs and purely central MAEs have been described in this report. The literature suggests that distinctions are required also among purely central aftereffects, which seem to differ in their durations and their strengths depending on the characteristics of the stimuli used to induce them. For instance, Blakemore and Julesz (1971) reported that the duration of their depth aftereffect, produced by static random-dot stereograms, was dependent on viewing time, whereas its strength, measured by the adapting disparity necessary to cancel the aftereffect, was not. By comparison, the duration of MAEs produced by analogous cyclopean stimuli, as used by Papert (1964) and in the present study, is not dependent on viewing time. Further, Anstis and Moulden (1970) noted that although their dichoptic MAEs were less pronounced than their monocular MAEs, the former predominated under viewing conditions in which they were in competition. Finally, Wolfe and Held (1983) also distinguished between the magnitude and duration of MAEs induced by a moving random dot display. They found that the magnitude of the MAE was less under binocular viewing than under monocular viewing when MAE magnitude was judged but not when MAE duration was judged.[1] These observations, taken together with the differences between binocular and purely central MAEs described earlier, are evidence of the complexities within the neural pathways mediating central MAEs. There has been a tendency to group various MAE phenomena together presumably to allow relatively simple models to explain them. A better approach might be to consider the complexities in the observed MAEs as an indication that the underlying anatomical complexities of the primate visual system (cf., Van Essen & Maunsell, 1983) are amenable to psychophysical study.

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[1] By the criteria established for the present effort, Wolfe and Held's (1983) stimuli are binocular, while Papert's (1964) are purely central. Wolfe and Held cite the short duration of both Papert's MAE and their own as evidence of a common process. However, the short duration reported by Papert is an invariant attribute of his MAE while the short duration of the Wolfe and Held aftereffect is probably attributable to a short viewing time and the use of a low density dot display.

EXPERIMENT II: SELECTIVE RIVALRY SUPPRESSION IN BINOCULAR VIEWING OF DYNAMIC VISUAL NOISE

Introduction

As discussed earlier, a perception of depth and coherent motion results if an interocular luminance difference is introduced during the binocular viewing of dynamic visual noise (Ross, 1974; Tyler, 1974). Several explanations for this DVN stereophenomenon have been suggested, and studies designed to distinguish among these explanations have represented the preponderance of research on this topic (Falk & Williams, 1980; Mezrich & Rose, 1977; Neill, 1981; Tyler, 1977).

The DVN stereophenomenon is also a potentially useful tool for the study of centrally mediated perception. In the present experiment, the DVN stereophenomenon was used to assess the selectivity of binocular rivalry. The results of several previous studies suggest that binocular rivalry suppression is non-selective in that several aspects of the visual stimulus can be suppressed simultaneously (Blake & Fox, 1974; Fox & Check, 1968; Hollins & Leung, 1978). Here it has been determined whether the rivalry suppression elicited by presenting differently colored stimuli to the two eyes would also suppress the information necessary to produce the binocularly mediated perception of movement and depth characteristic of the DVN stereophenomenon.

Method

Observers. Data were obtained from two of the observers (JH and DW) described in EXPERIMENT I.

Apparatus. The apparatus was identical to that used in EXPERIMENT I except that a red filter (Corning Glass #2404) was used in place of the series of neutral density filters. The red filter reduced the luminance of the DVN display to 0.4 fL.

Procedure. First the observer was permitted 4 to 5 minutes of adaptation to the display illumination and dynamic noise, then the red glass filter was placed in front of the observer's right eye in order to induce the perception of movement and depth as well as binocular rivalry. The observer used a hand operated digital timer to indicate when no trace of red appeared in the display. Four trials were run, each consisting of 10 one-minute intervals.

Results

When viewing the DVN display with a red filter over their dominant eye, both observers perceived a recessed plane of dots (pixels) moving in the direction of the unfiltered eye and a less well defined protruding plane of dots moving in the opposite direction. Both observers chose to attend to the recessed plane which they reported to be more prominent. The red filter induced binocular rivalry resulting in the display appearing alternately red and gray. It proved difficult for the observers to judge when the unfiltered eye was suppressed, that is, to judge the saturation of the red display. However, all observers could judge with confidence when the filtered eye was suppressed, that is, when no trace of red appeared in the display. The rivalry suppression data for both subjects are shown in Figure 2. As noted earlier, both observers saw movement and depth in the DVN display throughout the rivalry cycle (data at top of Figure 2). The percentage of each one minute test interval during which each observer saw no color in the DVN display is displayed at the bottom of Figure 2. For observer JH (circles), complete color suppression occurred for an average of 3.5 seconds (SD = 1.05) over each one-minute interval. For observer DW (squares), the average was 4.6 sec (SD = 1.22).

Discussion

The present data indicate that the rivalry suppression induced by color difference is selective in that the color information from the filtered eye can be suppressed while the information from that eye which contributes to the perception of movement-in-depth is not suppressed. These results are consistent with those of Treisman (1962) who found that color information could be suppressed without adversely affecting the fusion of stimuli in a stereoscope. Similarly, Julesz & Miller (1975) demonstrated the independence of spatial frequency channels participating in binocular fusion or rivalry. Other investigators (Blake & Fox, 1974; Fox & Check, 1968; Hollins & Leung, 1978) have concluded, however, that rivalry is a unitary process which simultaneously suppresses a wide range of visual stimuli. These contradictory positions suggest that a finer distinction must be made as to the neural sites of binocular fusion, binocular rivalry, and stereopsis. The importance of such a distinction has recently been demonstrated by Smith, Levi, Harwerth, and White (1982) who found that binocular rivalry attenuates opponent-color information much more than does luminance information. Color and movement information appear to be processed separately (cf. Anstis, 1980), and thus, the differential attenuation phenomenon reported by Smith et al. may also account for the present results.

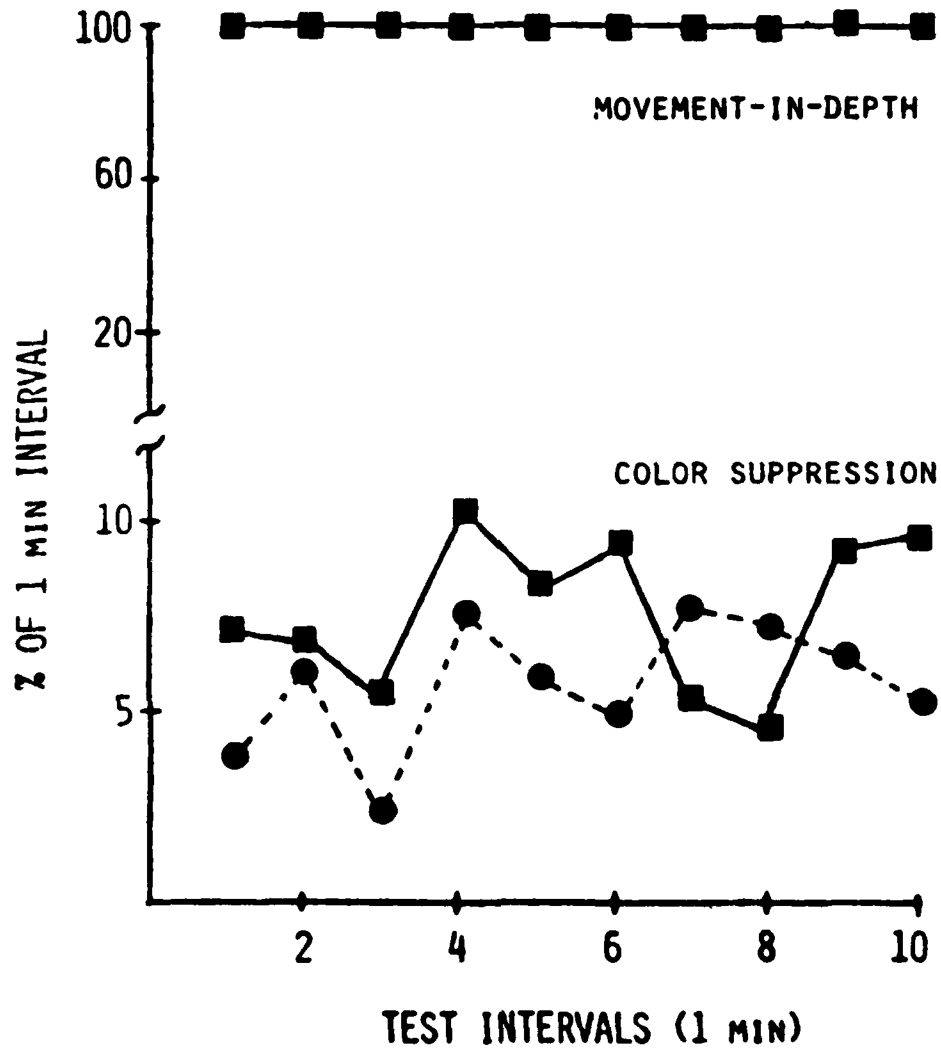

Figure 2. Percentage of each one minute test interval during which each observer (DW, squares; JH, circles) saw no color in the binocularly viewed DVN display.

EXPERIMENT III: ACCELERATION PERCEIVED WITH DYNAMIC VISUAL NOISE

Introduction

When a field of dynamic visual noise (DVN) is binocularly viewed with an interocular delay or intensity difference, it appears as coherent motion and depth (Ross, 1974; Tyler, 1974). Most observers see two counter directionally moving textured planes separated in depth (Geri & Zeevi, 1982; Mezrich & Rose, 1977), with the front plane moving laterally in the direction of the filtered eye, and the back plane moving in the opposite direction. Observers can estimate its velocity while attending to one of the moving planes and fixating a stationary point superimposed on it. Alternatively, they can track it, in which case they report that the perceived velocity appears to be greater than that estimated during fixation. This qualitative general observation was also previously reported (Falk & Williams, 1980; Tyler, 1974). Furthermore, it has been noticed that this phenomenon is associated with a gradual increase in perceived velocity -- i.e. the field of dots, or textured plane, actually seems to accelerate when tracked.

Since the smooth pursuit is controlled by perceived motion relative to the head (Steinbach, 1976; Young & Stark, 1963), eye movement measurements should provide a physiological correlate of the acceleration percept. Further, since an efferent copy of the oculomotor control signal is believed to be fed back and to carry a correction signal (Helmholtz, 1962), eye movements may influence the perceived velocity. Therefore, the trajectories of eye movements of observers were measured, while they tracked one of the moving planes, and their maximum velocity was compared with the perceived velocity estimated while fixating on a stationary point in the same plane.

Apparatus and Procedure

Dynamic visual noise has been generated in a variety of ways (Falk & Williams, 1980; MacDonald, 1977; Mezrich & Rose, 1977; Ross, 1974; Tyler, 1974). Of these, the adopted method involved detuning a black and white television receiver, subtending a visual angle of about 13 degrees horizontally when viewed from a distance of 56 cm. The mean luminance was 25 fL, and the contrast was 60%.

A second display, situated at a right angle to the TV monitor, was superimposed on the visual field of the right eye with a beam splitter (Figure 3), displaying a point moving at constant velocity, or a traveling square-wave grating of spatial frequency matched to the

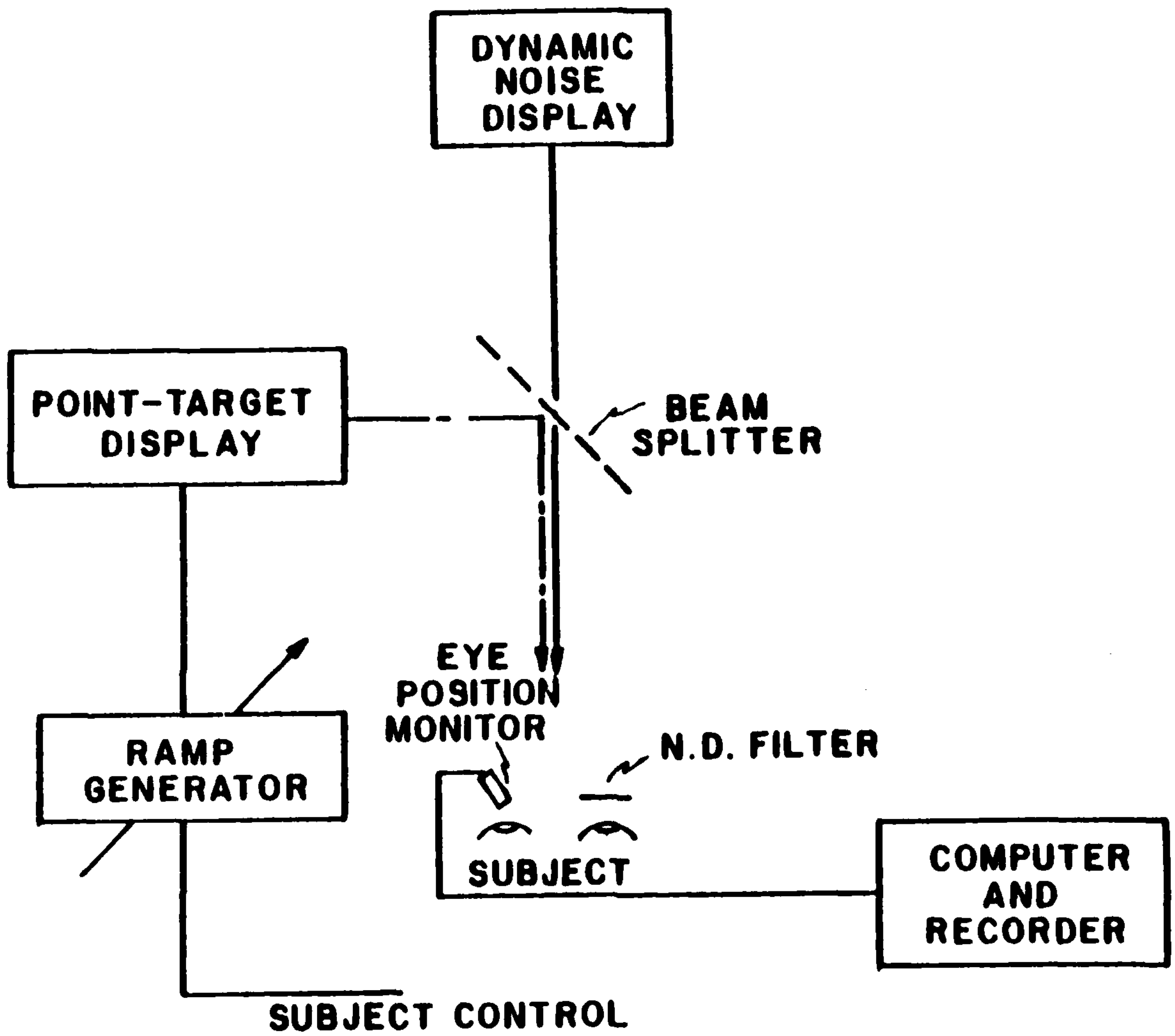

Figure 3. Apparatus used to estimate the perceived velocity induced by visual dynamic noise with interocular intensity difference in fixation and tracking modes of observation.

grain-size of the visual noise. A neutral density filter was placed in front of the right eye, so that the total relative attenuation was equivalent to 1.3 neutral density units. Movement of the left eye was monitored using an infrared limbus tracking device (bandwidth 1000 Hz).

Six subjects participated in the experiments -- three having previous experience with the DVN stereophenomenon and the others observing it for the first time. They viewed the display with head movements minimized by a headrest; in addition, a bite bar was used for the eye movement recordings. About one minute was allowed for adaptation to the dynamic noise, until coherent movement was reported. The moving point was then superimposed. Subjects were instructed to match the velocity of the repetitive moving point with that of the perceived recessed plane by adjusting the frequency of a saw-tooth generator. A stationary fixation point was used to minimize tracking of the moving point or perceived plane.

Next the eye-movement monitor was calibrated, in preparation for the tracking experiment, by having the subject fixate on the left and right edges of the display as well as on its center fixation-point. Subjects were asked to track the perceived coherent movement, while the left eye movements were monitored and sampled by a PDP 11/34 at a rate of 200 samples per second (thus reducing the effective bandwidth to 100 Hz). Following the experiment, subjects were asked to describe the qualitative characteristics of the movement perceived in the tracking mode.

Results

When the neutral density filter was placed over one eye, all observers reported the appearance of coherent motion and depth. The most common description of the perceived effect was that of two counter directionally moving textured planes separated in depth. Occasionally, though, subjects described the effect as that of a distribution in depth of moving planes, similar to the description reported by Tyler (1974). While fixating on the center of the dynamic visual noise display, all observers reported that they could selectively attend one of the two perceived moving planes. For novice subjects, the velocity-matching task proved to be more difficult because of the tendency to track the moving point, as was reflected in the eye-movement measurements. The first estimate was, therefore, much higher than the subsequent estimates and was excluded in the calculation of the mean velocity. (A typical complaint, under these circumstances of short episodes of pursuit eye movements, was that the velocity changed as soon as a match was achieved.) In subsequent sessions, with the subjects encouraged to take their time and strive for improved fixation, lower estimates were consistently obtained. Each of the velocities in the left-hand column of Table 2 represents the mean of two to five sessions. The means fall within the range of velocities obtained in other studies (Falk & Williams, 1980; Geri & Zeevi, 1982).

Table 2. Comparison of Velocities Induced in Fixation and Tracking Modes

Subject	Velocity Estimate in Fixation Mode Degrees/second	Maximum Induced Velocity in Tracking Mode Degrees/second
AM	3.5	38
JM	3.5	25
IM	2.0	30
JW	2.1	42
JI	*	32
YZ	5.3	47

*Subject JI found it difficult to match these velocities while fixating the center of the display.

Tracking the apparent movement was not an easy task for novice subjects, but after a few trials, they succeeded in generating smooth pursuits with little saccadic interruption. The observers could not produce smooth eye movements without appropriate visual stimuli. Invariably all observers reported an increase in perceived velocity due to tracking, some describing the effect as an abrupt increase far beyond the velocity perceived during fixation as though it were an all-or-nothing effect; other observers reported a gradual increase, indicating a continuous acceleration. Insofar as inferences about perceived velocity are possible from eye movement trajectories, the latter appears to be a better description of the phenomenon (Figure 4). The maximum velocity recorded during tracking was in the range of 25 to 50 degrees per second -- about a tenfold increase compared with the velocity estimated in the fixation mode. Each of the velocities summarized in the right-hand column of Table 2 represents the mean of 6 to 12 maxima of the derivatives computed for saccade-free tracking responses. Significantly, even over such a short distance of less than 10 degrees, the smooth-pursuit system accelerated the eyes somewhat beyond the upper limit hitherto believed possible (Young, 1981).

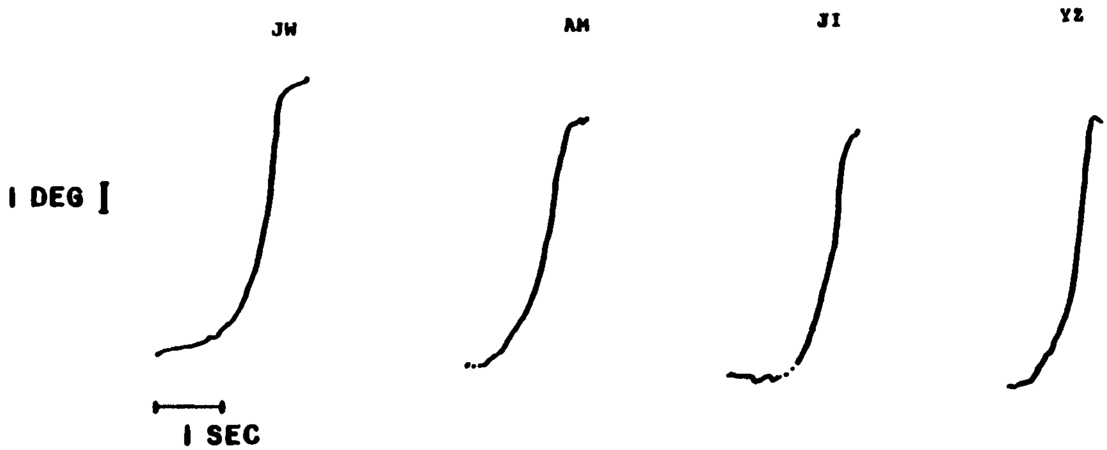

Figure 4. Typical examples of eye movement trajectories recorded during tracking of one of the perceived moving textured planes. The trajectories exhibit acceleration with exponential time course, decelerating towards the edge of the dynamic noise display. Dotted lines indicate filtering of blinks.

Discussion

Tyler (1974) was the first to observe that the movement aspect of the DVN stereophenomenon is enhanced by tracking, but he did not specify the conditions. Similarly, Ward and Morgan (1978) reported that the dots of the DVN stereophenomenon appear to move more rapidly when tracked. This observation was substantiated by Falk and Williams (1980) who reported that the more they attempted to track the coherent motion, the higher the velocity appeared. They also correctly argued that the perceived velocity derives from the combination of eye velocity and other sources of movement information, but stopped short of the conclusion that this situation results in a perceived acceleration along with its concomitantly driven accelerated eye movement.

It was previously shown by Steinbach (1976) that a centrally derived motion percept can provide a sufficient control signal for the pursuit system. The results from this experiment (Figure 4) corroborate this concept and also complement those of Dimitrov, Yakimoff, Mateef, Mitrani, Radil-Weiss, & Bozkov, (1976) on the saccadic movement by showing that the pursuit system can track visual movement that does not exist monocularly. In this regard, the present experiments are similar to those of Steinbach and Anstis (briefly discussed by Anstis (1980)), who generated moving stereo gratings, using Julesz' technique of dynamic random-dot stereocinematography, and who observed smooth tracking eye movements. It should be noted, however, that with the DVN here, no explicit positional or form information exists either monocularly or at the level of cyclopean perception. The component of the perceived velocity induced by the interocular intensity difference is, therefore, independent of eye position, and eye movements can in no way reduce nor compensate for it. The unity negative feedback loop is, under these circumstances, functionally opened as in other open loop situations (Robinson, 1965; Young & Stark, 1963; Zeevi, Peli, & Stark, 1979), since the efferent copy of the eye-movement command signal closes a positive feedback loop (Figure 5). When an attempt is made to track the induced movement, the eye velocity is added to the perceived velocity. This information in turn generates a new eye-movement command signal of higher velocity. Thus, this positive feedback loop gives rise to a perceptual effect of acceleration of the moving textured plane. This effect is reflected in exponential trajectory of eye movements.

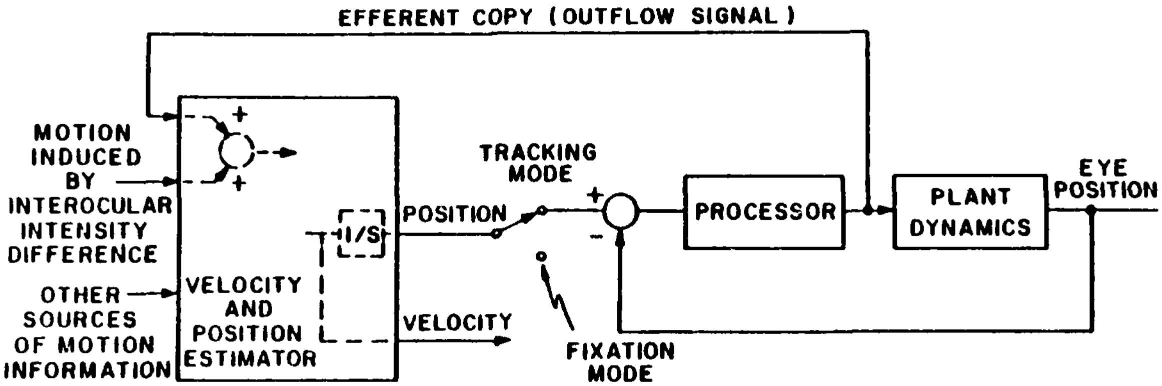

Figure 5. Simplified scheme depicting the basic hypothesis of how the efferent copy gives rise to a perceptual acceleration during tracking of motion induced by dynamic visual noise with inter-ocular intensity difference. (For further explanation see text.)

EXPERIMENT IV: VERGENCE AND ACCOMMODATION TO PERCEIVED DEPTH

Introduction

Under most real-life and experimental conditions, a physical change in the retinal image provides the relevant stimulus for oculomotor responses. However, recent work has demonstrated that perceptual stimuli, which do not exist at the retinal level, are sufficient to elicit certain types of eye movements. For instance, it has been shown that perceived motion can be more important than retinal motion as a stimulus for smooth pursuit (Heywood, 1973; Steinbach, 1976; Yasui & Young, 1975) and that saccadic eye movements can be elicited by cyclopean contours which do not exist at the retinal level (Dimitrov et al., 1976).

The present study addresses the question of whether centrally-produced, as opposed to retinal, stimuli are sufficient to elicit vergence eye movements and accommodation. The vergence system is by definition binocular and thus may be expected to react differently to retinal stimuli as opposed to stimuli which act at or central to the neural locus of stereopsis. The central stimulus chosen was the depth planes associated with the DVN stereophenomenon (Tyler, 1974). This phenomenon is easily produced and provides form-free depth stimuli. These stimuli are used here in an attempt to produce accurate vergence movements without retinal disparity.

Method

Subjects. Both subjects were trained observers and both were aware of the purpose of the study. Subject DR was a 27 year old, male emmetrope. Subject KC was a 37 year old, male myope whose vision was corrected by trial lenses (-1.5 diopters) placed before both eyes.

Apparatus. A diagram of the apparatus (top view) is shown as Figure 6. Static accommodation and vergence measurements were obtained using a haploscope optometer (cf., Ciuffreda & Kenyon, 1983) consisting of two optical channels. Each channel consists of a tungsten light source (S_L or S_R), a Badal lens (L_L or L_R, each +8.5D), and a beamsplitter (B_L or B_R). The light sources could be translated along the optical channel axis for measurement of accommodation. Each channel of the optometer could also be rotated about the center of rotation of the eye (in the plane of Figure 6) to obtain vergence measurements. Measurements were accurate to at least $\pm$ 0.25 diopters and $\pm$ 0.12 degrees.

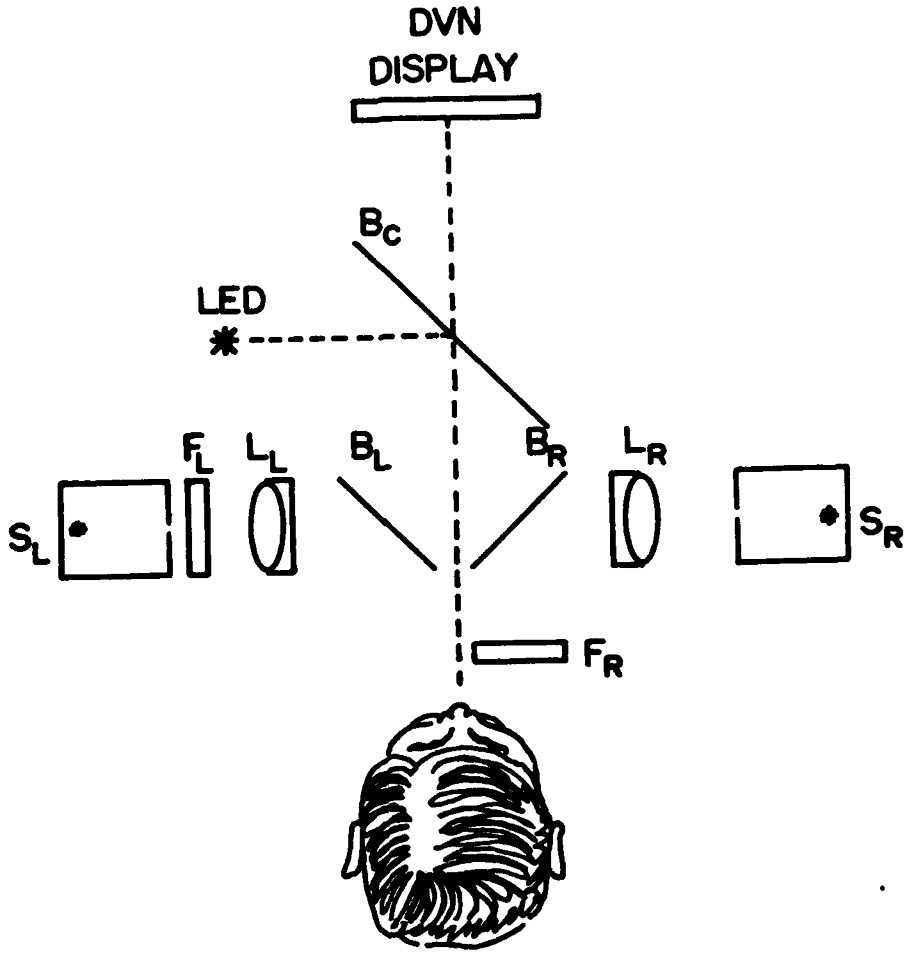

Figure 6. A diagram of the apparatus used for the vergence, accommodation, and depth measurements. Included are a haploscope optometer, consisting of light sources (S_L and S_R), lenses (L_L and L_R), and beamsplitters (B_L and B_R), and a movable LED which was superimposed on the DVN display by beamsplitter, B_C.

The visual display consisted of depth stimuli produced by binocular viewing of the dynamic visual noise of a detuned black and white television receiver (Daytron Model DT525) located 28.5 cm from the observer. The DVN depth stimuli were obtained (cf., Tyler, 1974) by attenuating the input to the observer's right eye with a neutral density filter placed at F_R. The observers reported seeing planes of moving dots, with the closer planes moving in the direction of the filtered eye, and the farther planes moving in the opposite direction. The farthest plane appeared most distinct to both observers (cf., Falk & Williams, 1980), although the nearest plane could be accurately localized also. These two planes were used as the depth stimuli for all measurements. Depth estimates were obtained using a red LED mounted on a sliding platform. An image of the LED was binocularly superimposed on the DVN display by a large beamsplitter (B_C).

The luminance of the DVN display as viewed through the beamsplitters was 1.5 fL and was the luminance presented to the left eye. A 2.1 neutral density filter was used at F_R resulting in a display luminance of 0.12 fL reaching the right eye. For all measurements for which filter F_R was used, a filter, F_L, of the same density was used to keep the Badal light sources at the same intensity.

Procedure. The subjects first adapted for 5 minutes to the DVN display. While in the testing position, as determined by adjustment of a chin and head rest, the subjects rotated the right channel of the optometer such that the image of S_R appeared at the center of the relevant stimulus display. The position of the right channel was not altered again with vergence measurements obtained by rotational adjustment of the left channel only.

Following adaptation, a 2.1 neutral density filter was placed at F_R in order to induce the perception of depth in the DVN display. Each subject then viewed either the near or the far depth plane and adjusted the positions of L_L to obtain the sharpest smallest image of the centered light source. The left channel of the optometer was then rotated to obtain vertical alignment of the image of L_L with that of L_R. The resulting vergence and accommodation measures were recorded, and the positions of L_L and the left channel were changed by the experimenter before the subject made similar settings to the other depth plane. This procedure was repeated to obtain eight vergence and accommodation measures to both the near and far depth planes. Estimates of the perceived separation of the DVN depth planes were obtained by asking each subject to adjust the position of the red LED that was superimposed on the depth stimuli through beamsplitter B_C. Ten such measurements were obtained to both the farthest and nearest DVN dot-planes and the DVN display as it appeared with filters F_R and F_L removed.

Results

Shown in Figure 7 (top) are the vergence responses of the left eye of both subjects to the perceived far and near DVN depth planes. For observer KC, vergence to the far depth plane was 5.83 degrees (SD = 0.089, n = 8) and vergence to the near depth plane was 5.98 degrees (SD = 0.046, n = 8). The difference in the vergence response to the far and to the near depth planes was statistically significant ($p < 0.001$). For subject DR, vergence to the far depth plane was 5.74 degrees (SD = 0.141, n = 8) and vergence to the near depth plane was 5.97 degrees (SD = 0.059, n = 8). Again, the difference in vergence to the two planes was statistically significant ($p < 0.002$).

Shown in Figure 7 (bottom) are the left eye accommodative responses of both subjects to the perceived far and near DVN depth planes. For subject KC, the accommodative response was 2.023 diopters (SD = 0.237, n = 8) to the far depth plane and 2.021 diopters (SD = 0.163, n = 8) to the near depth plane. The difference in these responses was not statistically significant ($p > 0.95$). For subject DR, the accommodative response was 2.553 diopters (SD = 0.323, n = 8) to the far depth plane and 2.783 diopters (SD = 0.205, n = 8) to the near depth plane. The difference in these responses was not statistically significant ($p > 0.10$).

The results of the LED depth measurements indicated that both subjects perceived the actual DVN display to be located between the far and near DVN depth planes. However, the depth planes were not seen as equally spaced about the DVN display. For subject KC, the DVN display appeared 1.2 mm in front of the far depth plane and 7.3 mm behind the near depth plane. For subject DR, the DVN display appeared 2.8 mm in front of the far depth plane and 5.9 mm behind the near depth plane.

Discussion

The primary stimulus for the control of vergence eye movements is generally considered to be retinal disparity. The data of Figure 7 (top) demonstrate that perceptual stimuli which provide no retinal disparity are sufficient to elicit accurate vergence movements. Although the perception of depth in the DVN display may be the result of binocular disparity (Tyler, 1974), the disparity mechanism must be acting on information originating at some binocular site. The only alternative explanation would be that volitional factors are mediating the control of

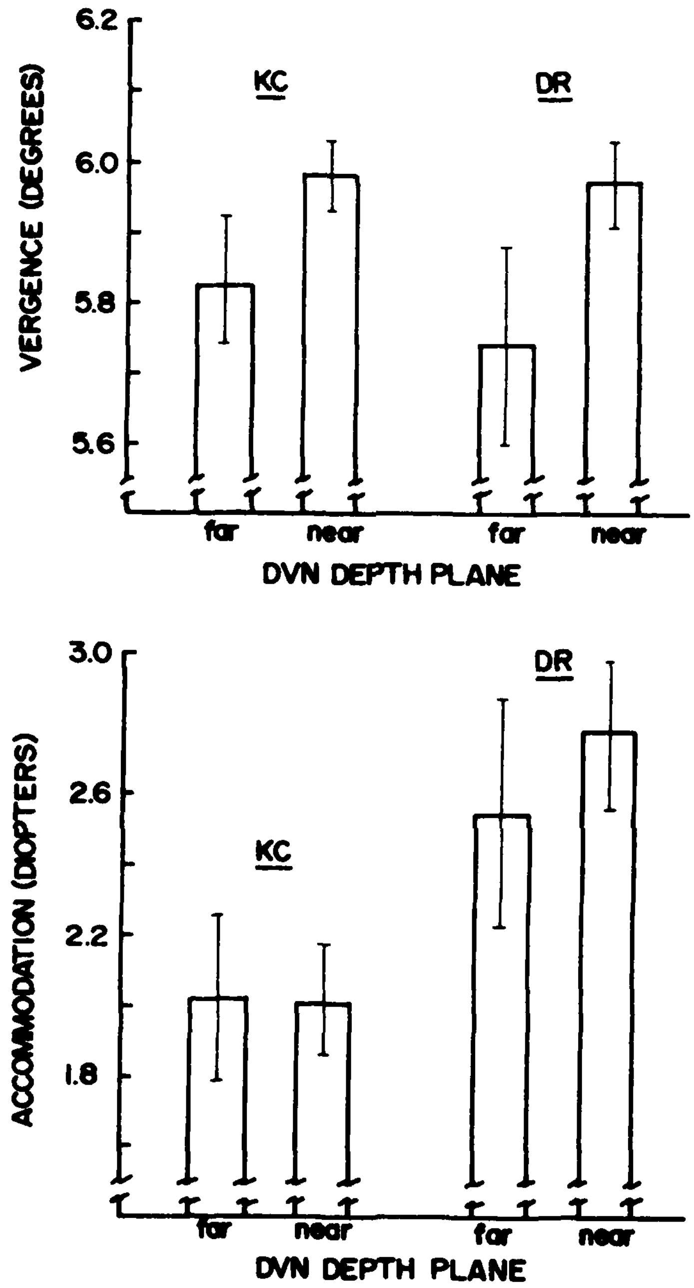

Figure 7. Vergence (top) and accommodation (bottom) each plotted as a function of the DVN plane (far or near) viewed by the two observers. The error bars represent ± 1 standard deviations.

these eye movements. Although the existence of such volitional factors seems to be generally accepted, it has not been experimentally verified to our knowledge. In any case, volitional control would probably not result in the accuracy evident in the data of Figure 7.

Neither of our subjects showed a significant change in accommodation when they shifted fixation between the near and far DVN planes. As indicated by the LED depth estimates, the perceived distance between the two depth planes was only about 8.6 mm. This corresponds to a 0.08 diopter change in accommodation which is below the resolution of our optometer. There was a difference of 0.23 diopters in the accommodative response of subject DR to the two depth planes. Although this difference was not statistically significant, it was larger than would be expected given the perceived distance between the far and near planes. This may be an indication of a quantitative difference in the accommodative response to real and perceived depth. However, the limited resolution of the present apparatus and the fact that no attempt was made to measure vergence and accommodation independently prevent the conclusion that centrally-produced depth is sufficient to mediate an accommodative response.

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APPENDIX A: THE RAW DATA OF EXPERIMENT I AND A SUMMARY OF THE ANALYSIS OF VARIANCE PERFORMED

Part 1. Perceived DVN Velocity as a Function of Neutral Density Attenuation of the Right Eye for Each of the Three Subjects

ND Attenuation

Subject GG - DVN Motion

Trial	1.0	1.3	1.5	1.7	2.0	2.3	2.5
1	3.2	3.9	4.9	4.1	5.3	4.8	5.4
2	3.8	3.3	4.8	4.3	5.1	3.8	5.4
3	4.4	3.3	3.8	5.1	5.1	5.0	4.9
4	4.5	4.6	4.8	5.4	3.6	5.3	4.7
5	3.7	3.7	4.4	5.5	5.6	5.1	4.3
6	4.2	4.2	3.4	4.4	4.9	5.4	4.4
7	4.5	3.9	4.3	3.9	5.1	4.4	5.8
8	3.7	4.1	5.6	5.1	5.0	4.2	4.8
Mean	4.00	3.88	4.50	4.73	4.96	4.75	4.96
SD	.472	.443	.687	.620	.590	.566	.526
Ex	32.000	31.000	36.000	37.800	39.700	38.000	39.700
Ex^2	129.560	121.500	165.300	181.300	199.450	182.740	198.950

Subject JH - DVN Motion

Trial	1.0	1.3	1.5	1.7	2.0	2.3	2.5
1	4.2	4.1	3.2	3.3	3.0	4.4	3.8
2	3.2	3.8	3.2	3.9	4.0	4.0	3.9
3	3.2	3.1	3.8	4.1	3.8	3.9	4.0
4	3.8	3.1	3.6	4.7	3.3	3.3	4.4
5	3.1	3.8	2.8	3.6	4.2	3.6	3.6
6	2.9	2.8	3.6	4.5	3.8	3.1	2.9
7	4.0	3.3	3.7	4.5	3.7	3.8	3.3
8	3.0	3.9	3.2	3.2	4.7	4.0	4.5
Mean	3.43	3.49	3.39	3.98	3.81	3.76	3.80
SD	.498	.470	.340	.573	.522	.417	.535
Ex	27.400	27.900	27.100	31.800	30.500	30.100	30.400
Ex^2	95.580	98.850	92.610	128.700	118.190	114.470	117.520

Subject DW - DVN Motion

1	3.5	3.6	4.3	3.9	4.6	4.5	3.9
2	4.1	3.8	4.5	3.8	4.6	4.8	4.4
3	4.3	3.8	3.8	4.5	3.3	4.1	5.1
4	3.3	4.8	3.0	4.4	3.9	3.7	5.1
5	3.2	4.2	3.1	4.4	4.1	3.8	4.9
6	3.8	3.4	3.4	3.5	4.2	5.0	5.0
7	3.0	3.7	3.1	3.3	3.9	5.2	4.6
8	3.0	4.8	4.0	3.6	4.9	4.8	5.7
Mean	3.53	4.01	3.65	3.93	4.19	4.49	4.84
SD	.495	.536	.583	.459	.508	.562	.540
Ex	28.200	32.100	29.200	31.400	33.500	35.900	38.700
Ex^2	101.120	130.810	108.960	124.720	142.090	163.310	189.250

Part 2. Perceived Velocity of Motion Aftereffect as a Function of the Neutral Density Attenuation Used to Induce the DVN Stereophenomenon for Each of the Three Subjects

Subject GG - DVN Aftereffect

1	4.9	5.3	5.3	4.3	4.4	4.3	5.8
2	5.5	3.9	4.8	4.0	4.6	4.6	4.2
3	3.7	4.5	4.3	4.9	5.7	5.2	5.1
4	4.3	4.7	4.4	5.3	5.7	5.6	5.1
Mean	4.60	4.60	4.70	4.63	5.10	4.93	5.05
SD	.775	.577	.455	.585	.698	.585	.656
Ex	18.40	18.40	18.80	18.500	20.400	19.700	20.20
Ex^2	86.44	85.640	88.980	86.590	105.500	98.050	103.300

Subject JH - DVN Aftereffect

1	4.3	3.9	4.8	4.2	4.0	3.8	4.2
2	3.8	4.1	3.4	4.9	3.7	4.8	4.8
3	2.9	3.7	4.6	3.7	3.0	5.1	3.2
4	4.2	3.0	3.3	3.5	4.3	3.5	3.8
Mean	3.80	3.68	4.03	4.08	3.75	4.30	4.00
SD	.638	.479	.785	.624	.557	.770	.673
Ex	15.20	14.70	16.100	16.300	15.000	17.200	16.000
Ex^2	58.98	54.710	66.650	67.590	57.180	75.740	65.360

Subject DW - DVN Aftereffect

1	3.7	4.6	3.6	4.8	5.4	5.0	3.9
2	4.3	4.6	4.4	3.6	4.5	4.2	4.9
3	4.7	3.6	4.2	3.1	3.8	3.8	5.2
4	5.1	5.5	5.4	3.9	5.1	5.5	4.3
Mean	4.45	4.58	4.40	3.85	4.70	4.63	4.58
SD	.597	.776	.748	.714	.707	.768	.585
Ex	17.800	18.300	17.600	15.400	18.800	18.500	18.300
Ex^2	80.280	85.530	79.120	60.540	89.860	87.330	84.750

Part 3. Summary of Analysis of Variance

Source	SS	df	MS	F	p
MOTION					
between treatments (ND)	1.98	6	0.33	5.50	.01
between blocks (subjects)	2.67	2	1.34	22.33	.001
residual	0.76	12	.06		
Total	5.41	20			
AFTEREFFECT					
between treatments (ND)	0.46	6	.077	1.53	.20
between blocks (subjects)	2.58	2	1.29	25.8	.001
residual	0.60	12	.05		
Total	3.64	20			

APPENDIX B: THE RAW DATA OF EXPERIMENT IV

Part 1. Vergence Responses (in degrees) to the Far and Near Depth Planes for Each Subject

Trial	Subject KC far	Subject KC near	Subject DR far	Subject DR near
1	5.95	5.95	5.60	5.90
2	5.75	6.00	5.90	6.00
3	5.90	6.00	5.80	6.00
4	5.70	5.95	5.80	6.05
5	5.80	6.05	5.90	6.00
6	5.85	5.90	5.50	6.00
7	5.90	6.00	5.70	5.90
8	5.75	6.00	5.70	5.90
mean	5.825	5.981	5.738	5.969
SD	.0886	.0458	.1408	.0594

Part 2. Accommodative Responses (in diopters) to the Far and Near Depth Planes for Each Subject

Trial	Subject KC far	Subject KC near	Subject DR far	Subject DR near
1	2.38	2.04	2.12	2.83
2	2.30	2.08	2.12	2.67
3	2.00	1.65	2.59	2.59
4	1.83	2.17	2.55	2.55
5	2.12	2.12	2.59	2.98
6	1.87	2.08	2.86	3.15
7	1.68	1.95	2.53	2.67
8	2.00	2.08	3.06	2.82
mean	2.023	2.021	2.553	2.783
SD	.2369	.1628	.3226	.2050

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